Excel for Water system Hydraulic Analysis Tool (X – WHAT)

User Guide

Toll version: 0.0.1

Guide version: 0.0.1

Developer: Marcus Nóbrega

User guide by Igor Matheus Benites

All software, figures, and data can be freely downloaded in

https://github.com/marcusnobrega-eng/ETHA---Clone

Marcus Nóbrega Gomes Jr [a,b,c]

Igor Matheus Benites [a]

Salma M. Elsherif [d]

Ahmad F. Taha[d]

Marcio H. Giacomoni [b]

[a] University of São Paulo, Department of Hydraulic Engineering and Sanitation, São Carlos School of Engineering.

[b] University of Texas at San Antonio, College of Engineering and Integrated Design, School of Civil & Environmental Engineering and Construction Management.

[c] University of Arizona, Department of Hydrology and Atmospheric Sciences

[d] Vanderbilt University, Department of Civil and Environmental Engineering.

- Accuracy: While every effort has been made to ensure the accuracy of the information, the document may contain errors or omissions.
- Updates: The document is subject to change without notice. Always refer to the latest version for current information.
- This is the first version of the user guide; it is intended to be simple and concise rather than a complete technical documentation.
- For technical aspects regarding the development and operation of the tool, consult the original publication (Currently Under Review).
- This project is fully open-source. Therefore, all functionalities of the spreadsheet will remain unblocked. However, executing the tool and making modifications to its configuration must be done at the user's own risk. Neither the authors nor the institutions with which they are associated can assume responsibility for program modifications, content, output, interpretation, or usage.

Summary

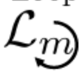
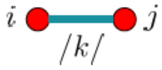
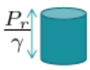
1.0 - Introduction

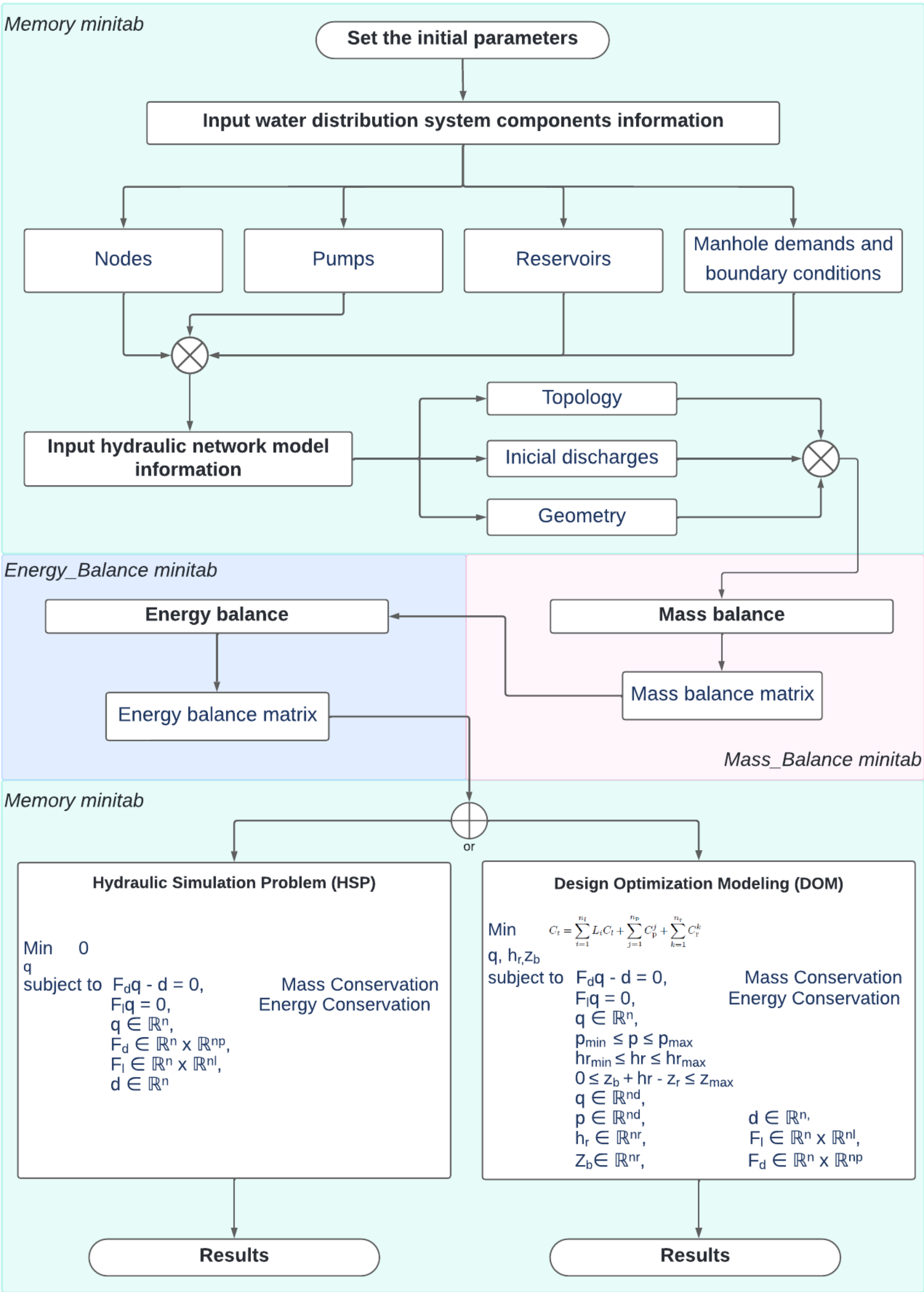
- Purpose: This guide serves as a comprehensive manual for the X - WHAT Model, an open-source tool for water distribution network design and optimization.
- Accessibility: Designed with user-friendliness in mind, it requires no coding expertise and utilizes Excel's built-in functions for modeling and simulation.
- Applications: Ideal for educational purposes, the guide facilitates the understanding of hydraulic modeling and network optimization in an accessible format.
- Structure: The manual is structured to provide step-by-step instructions, practical examples, and optimization techniques for effective water resource management.
- Not all figures and tables are labelled. Labels are used for convenience when necessary for citation in the text.

2.0 - WDNs components and topology

This section provides a brief overview of the main components within the water distribution network and the notation used (Table 1). Please note that the assumptions and notation described here apply to version 0.0.1 of the tool and may change for future versions.

Table 1 - WDN components and notation used.

Nodes 	- Include reservoirs, junctions, and tanks - Continuous numbered
Loop 	- Follow the clockwise convection
Links 	- Include pipes, pumps, and valves - Continuous numbered
	- Pipes: conveying elements that have a constant slope and is defined by the diameter (D), the length (L), and friction properties
	- Valves: all valves are assumed fully open.
	- Junctions: connects two or more links and is defined by an elevation value representing the link centering elevation from a reference datum
Pump 	- Not directly used for controlling network dynamics in this version - Considered for calculating energy costs
Tank 	- Storage elements that are defined by their piezometric head at their surface


Memory minitab
Set the initial parameters
Input water distribution system components information
Nodes
Pumps
Reservoirs
Manhole demands and boundary conditions
Input hydraulic network model information
Topology
Inicial discharges
Geometry
Energy_Balance minitab
Energy balance
Energy balance matrix
Mass balance
Mass balance matrix
Mass_Balance minitab
Memory minitab
or
Hydraulic Simulation Problem (HSP)
Min 0
q
subject to $F_d q - d = 0$, Mass Conservation
$F_l q = 0$, Energy Conservation
$q \in \mathbb{R}^n$,
$F_d \in \mathbb{R}^n \times \mathbb{R}^{np}$,
$F_l \in \mathbb{R}^n \times \mathbb{R}^{nl}$,
$d \in \mathbb{R}^n$
Design Optimization Modeling (DOM)
Min $C_t = \sum_{i=1}^{n_l} L_i C_l + \sum_{j=1}^{n_p} C_p^j + \sum_{k=1}^{n_r} C_r^k$
q, h_r, z_b
subject to $F_d q - d = 0$, Mass Conservation
$F_l q = 0$, Energy Conservation
$q \in \mathbb{R}^n$,
$p_{min} \leq p \leq p_{max}$
$hr_{min} \leq hr \leq hr_{max}$
$0 \leq z_b + hr - z_r \leq z_{max}$
$q \in \mathbb{R}^{nd}$,
$p \in \mathbb{R}^{nd}$,
$h_r \in \mathbb{R}^{nr}$,
$Z_b \in \mathbb{R}^{nr}$,
$d \in \mathbb{R}^n$,
$F_l \in \mathbb{R}^n \times \mathbb{R}^{nl}$,
$F_d \in \mathbb{R}^n \times \mathbb{R}^{np}$
Results
Results

The tool comprises three distinct minitabs: Memory, Mass_balance, and Energy_Balance. The matrices of mass balance and energy balance are entered in their respective minitabs. The memory minitab has the input data for all pipes, nodes, and reservoirs.

All cells that accept data input are marked in **white**. **Gray cells** contain automatically executed operations and should not be altered. However, it is recommended that users (especially in a classroom setting) explore the purpose of each cell and understand their interrelationships. The trace precedents and trace dependents options available in the "Formulas" tab of the toolbar are helpful aids for this task.

From now on, all values that appear in images, tables, and figures are related to the case presented by Huddleston 2024. This numerical case study depicts a larger network with 8 loops, 12 internal nodes, 2 reservoirs, and a total of 21 links. All nodes have the same elevation. Reservoir 1 (node 13) is 3.66 meters above Reservoir 2 (node 14). Demands are assessed at four nodes in the network, and the problem involves determining the discharges and flow directions in all pipes, subject to known reservoir head boundary conditions. Figure 1 illustrates the network schematics, and Table 2 provides information about the pipes.

Figure 1 - Network schematics of testing case (c), adapted from Huddleston (2004).

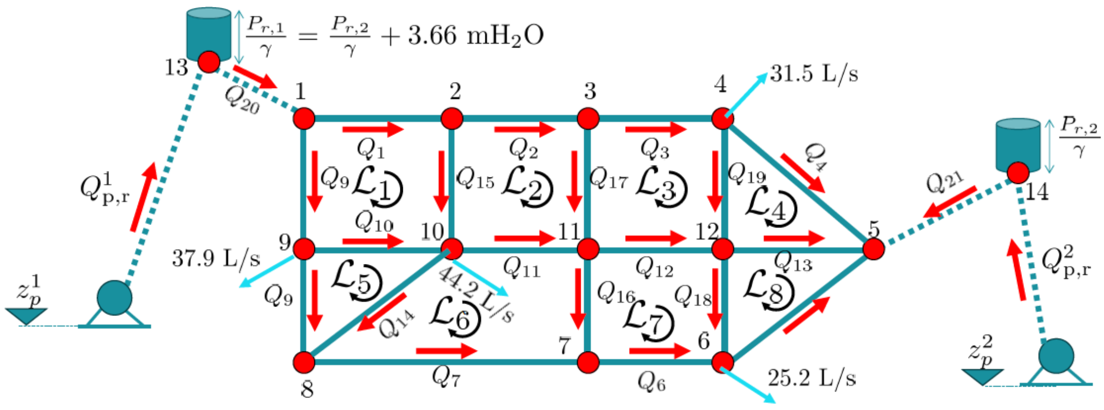


Table 2 - Input data for Huddlestone Network.

Link ID	D [mm]	L [mm]	ϵ [mm]	Q_h [L/s]
/1/	305	457.2	0.26	55.8
/2/	203	304.8	0.26	40.0
/3/	203	365.8	0.26	16.5
/4/	203	609.6	0.26	-10.3
/5/	203	853.4	0.26	-8.7
/6/	203	335.3	0.26	12.6
/7/	203	304.8	0.26	15.0
/8/	203	762	0.26	9.7
/9/	203	243.8	0.26	48.0
/10/	152	396.2	0.26	0.4
/11/	152	304.8	0.26	10.8
/12/	254	335.3	0.26	-7.4
/13/	254	304.8	0.26	-16.0
/14/	152	548.6	0.26	5.3
/15/	152	335.3	0.26	15.7
/16/	152	548.6	0.26	-2.4
/17/	254	365.9	0.26	23.6
/18/	152	548.6	0.26	4.0
/19/	152	396.2	0.26	-4.7
/20/	1000	25	0.26	103.7
/21/	1000	25	0.26	35.1

4.1 - Memory Sheet

4.2 - Defining the initial parameters

First, the user must define which method to use to calculate the head loss. The D-W method corresponds to the Hazen-Williams method, while the H-W method corresponds to the Darcy-Weisbach method. Next, several input fields must be filled in with variables relevant to the analysis. Figure 2**Error! Reference source not found.** shows part of the interface and Table 3 shows the description of each variable. The values depicted in Figure 2 are associated with the network described in Figure 1.

Figure 2 - Interface for setting the initial parameters.

ETHA - Clone Model

Excel Tool for Hydraulic Analysis - Closed Looped Networks

Head loss method	D-W	*Head loss method.* *H-W (Hazzen-Willians), D-W Darcy Weisbach*
ν	0,000001	*kinematic viscosity of the fluid in m^2/sec*
ρ	1000	*Density of the fluid in kg/m^3*
Num. of links	21	*Number of links*
Num nodes	14	*Number of nodes*
Num. Loops	8	*Number of loops*
Pc	0,2	*Cost of 1 kWh of Energy (USD/kWh)*
ir	6%	*Annual increase rate in energy*
Years	25	*Lifespan of the system*
Rate	12%	*Interest rate*
α	0%	*Operational cost rate*
k1	1,2	*Day Factor*
k2	1,5	*Hour factor*
Dtr	1	*Duration to fill the reservoir (days)*
Material Cost	60	*USD/m^2*
Vk	40	*Windspeed velocity (m/s)*
p	0,3	
q	60	*Specific head*

Table 3 - description of each variable

Variable	Description
D-W or *H-W*	Head loss method (H-W: Hazen-Williams; D-W: Darcy-Weisbach)
v	Represents the kinematic viscosity of the fluid in m^2/sec
ρ	Represents the density of the fluid, measured in kg/m^3.
Num. of links	Indicates the total number of links within the hydraulic network.
Num nodes	Refers to the total number of nodes or junction points within the network.
Num. Loops	Indicates the total number of loops within the hydraulic network.
Pc	Stands for the cost per kilowatt-hour (kWh) of energy in USD/kWh.
i_r	Represents the annual increase rate in energy costs, expressed as a percentage.
Years	Indicates the lifespan of the system being analyzed, measured in years.
Rate	Refers to the interest rate applicable to investments or loans related to the project, expressed as a percentage.
α	Represents the operational cost rate associated with maintenance and operation expenses over time; it's expressed as a percentage.
k_1	The day factor used for calculations related to daily operations or impacts within the system.
k_2	The hour factor, similar to k1 but applied on an hourly basis for more granular analysis.
Dtr	Duration to fill the reservoir, indicating the time required (in days) to completely fill up storage reservoirs within the system.
Material Cost	Refers to the cost per cubic meter (USD/m^3) associated with materials required for construction of the reservoirs.
V_k	Wind speed velocity (m/s) used to calculate mechanical stresses on structures exposed above the surface level (reservoirs).
p	p is an exponent that increases with the topographic elevation and can be estimated in terms of the wind speed

Figure 3 - Values relating the pipe diameters and the cost per meter of the links.

H	I	J	K
D [mm]	**Cost [USD/m]**	**D-W Rugosity [mm]**	**Hazzen-Willians Coef.**
25,4	2	0,26	130
50,8	5	0,26	130
76,2	8	0,26	130
101,6	11	0,26	130
152,4	16	0,26	130
200	23	0,26	130
254	32	0,26	130
304,8	50	0,26	130
355,6	60	0,26	130
406,4	90	0,26	130
457,2	130	0,26	130
508	170	0,26	130
558,8	300	0,26	130
609,6	550	0,26	130

The implementation cost is typically given by discrete values relating the pipe diameters and the cost per meter of the links. Users can set these values manually or use the default values already provided (Figure 3). For more details on the pipeline cost function, see the original publication (Under Review).

4.3 - Inserting water distribution system components information

Figure 4 displays the section of the interface dedicated to inputting node and pump information. Figure 5, on the other hand, presents the automatically calculated results based on the information entered.

Figure 4 - Node and pumps information input section.

Node Info			Pump Info					
Node	Elevation (m)	Node Type	n_p [h]	ηp	z_{pump} [m]	hg [m]	Qp-r [L/s]	Kp
1	100	Manhole						
2	100	Manhole						
3	100	Manhole						
4	100	Manhole						
5	100	Manhole						
6	100	Manhole						
7	100	Manhole						
8	100	Manhole						
9	100	Manhole						
10	100	Manhole						
11	100	Manhole						
12	100	Manhole						
13	100	Reservoir or Tank	12	0,85	95	26,19292562	137,8098589	336,78
14	100	Reservoir or Tank	12	0,85	95	22,53292562	47,25680782	5641,585329

Figure 5 - Calculations results for pumps.

Pump Info				
hf,pump [m]	Hm,pump [m]	Pot [kW]	Cost of Energy per Day (1000 USD)	Cost of Energy per year (1000 USD)
6,40	32,59	51,83	0,12	45,41
12,60	35,13	19,16	0,05	16,78

4.3.1 - Node information

Nodes	This column is automatically filled based on the number of nodes entered in the previous step (when defining the initial parameters). It represents the node index
Elevation	Node ground elevation from a reference Datum
Node Type	Select the node type from either “Manhole” or “Reservoir or Tank”. Reservoirs and tanks are considered equivalent for steady-state simulations

4.3.2 - Pump information

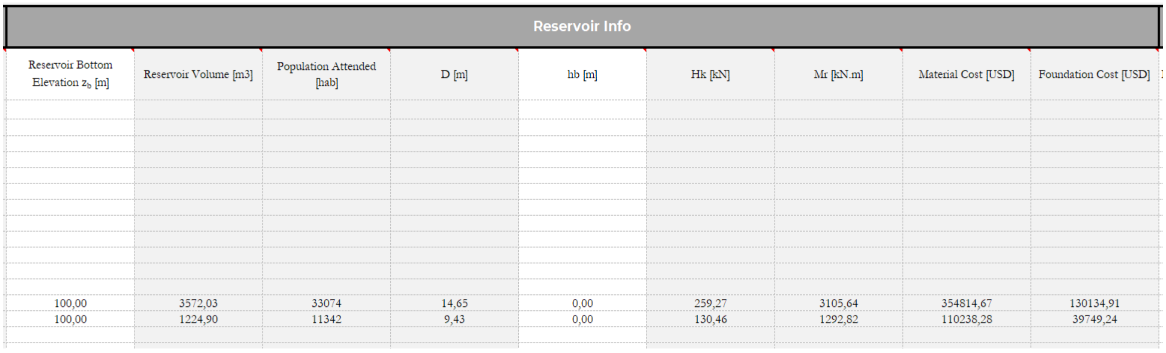
In this section, only the cells related to the node type previously selected as “Reservoir or Tank” should be filled out. This is because, in this version, pumps are not used for dynamic network control but solely for supplying the reservoirs.

Calculated and filled in automatically	
n_p [h]	Number of hours that the pump will be activated, per day
ηp	Pump efficiency
z_{pump}[m]	Ground elevation of the pump
hg [m]	Geometrical topographic difference between the ground pump elevation and ground reservoir elevation.
$Qp - r$ [L/s]	Pump flow discharge
Kp	Linear head loss coefficient for the pump head loss -> hf = kp * Q * |Q| ^ (n-1)
$hf, pump$ [m]	Head loss due to the friction from the pump to the reservoir
$Hm, pump$ [m]	Manometric head in the pump
$Pot\ [kW]$	Pump power
Cost of Energy per Day	Cost of pump energy per day in thousands of USD
Cost of Energy per year	Cost of pumping energy per year in thousands of USD

4.3.2 - Reservoir information

Figure 6 showcases the portion of the interface dedicated to inputting reservoir information. Note that only the **white** cells should be filled, and the information should be entered in the corresponding rows where, during the node information input, the option “Reservoir or Tank” is selected.

Figure 6 - Section of the interface dedicated to inputting the reservoir information.



Reservoir Info								
Reservoir Bottom Elevation z_b [m]	Reservoir Volume [m3]	Population Attended [hab]	D [m]	hb [m]	Hk [kN]	Mr [kN.m]	Material Cost [USD]	Foundation Cost [USD]
100,00	3572,03	33074	14,65	0,00	259,27	3105,64	354814,67	130134,91
100,00	1224,90	11342	9,43	0,00	130,46	1292,82	110238,28	39749,24

Calculated and filled in automatically	
Reservoir Bottom Elevation z_b $[m]$	Insert the reservoir or tank ground elevation
Reservoir Volume $[m^3]$	Reservoir volume, calculated in terms of the demand and k_2 factor
Population Attended [hab]	Equivalent population attended for the reservoir
D $[m]$	Reservoir diameter
hb $[m]$	Height from the ground * This can be set as a variable of the optimization problem.
Hk $[kN]$	Horizontal wind force
Mr $[kN.m]$	Wind bending moment at the foundation
Material Cost [USD]	Reservoir material cost
Foundation Cost [USD]	Reservoir foundation cost

4.3.2 - Manhole demands and boundary conditions information

Figure 7 displays the section dedicated to inputting demands for each of the nodes and the boundary conditions of the problem. Note that, for the demands at each node, positive values represent flows being withdrawn from the nodes, while negative values indicate flows entering the nodes.

Figure 7 - Section of the interface to inputting the manhole demands and to set the boundary conditions.

Manhole Demand	Boundary Conditions			
Demand (L/s)	Fixed Head?	Pressure (m)	Head [m]	hb + P/gamma [m]
0	0			
0	0			
0	0			
31,5	0			
0	0			
25,2	0			
0	0			
0	0			
37,9	0			
0	0			
44,2	0			
0	0			
-103,3573941	1	21,19292562	121,1929256	21,19292562
-35,44260586	1	17,53292562	117,5329256	17,53292562

Calculated and filled in automatically	
$Demand\ [L/s]$	Positive values take out flow from the nodes
Fixed Head?	If 1 $->$ the node has a fixed pressure boundary condition If 0 $->$ the pressure can vary. * For reservoirs, it has to be set to 1. * We can impose some nodes of the network to have specific values by fixing it (set to 1)
$Pressure\ [m]$	Head pressure considered when fixing the head * Can be set as a variable of the optimization problem
$Head\ [m]$	Total head
$hb + P/\gamma\ [m]$	Depth from the ground

4.4 - Inserting information from the hydraulic network model

Figure 8 shows the part of the interface where information about the topology of the network, the geometry of each link and the initial values for the discharges are entered.

Figure 8 - Section of the interface dedicated to inputting information about the hydraulic model

Topology				Decision Variable	*Geometry*		
Segment	Upstream Node	Downstream Node	Name	q(L/s)	L (m)	Real Diameter [mm]	Cost (USD) fitted
1	1	2	t. 1-2	55,53	457,2	305	21295
2	2	3	t. 2-3	39,85	304,8	203	6953
3	3	4	t. 3-4	16,39	365,8	203	8345
4	4	5	t. 4-5	-10,40	609,6	203	13906
5	6	5	t. 6-5	-8,75	853,4	203	19467
6	7	6	t. 7-6	12,46	335,3	203	7649
7	8	7	t. 8-7	14,89	304,8	203	6953
8	9	8	t. 9-8	9,61	762	203	17382
9	1	9	t. 1-9	47,82	243,8	203	5561
10	9	10	t. 9-10	0,32	396,2	152	6732
11	10	11	t. 10-11	10,72	304,8	152	5179
12	11	12	t. 11-12	-7,60	335,3	254	10734
13	12	5	t. 12-5	-16,30	304,8	254	9758
14	10	8	t. 10-8	5,28	548,8	152	9325
15	2	10	t. 2-10	15,68	335,3	152	5697
16	11	7	t. 11-7	-2,43	548,6	152	9322
17	3	11	t. 3-11	23,46	365,9	254	11714
18	12	6	t. 12-6	3,99	548,6	152	9322
19	4	12	t. 4-12	-4,71	396,2	152	6732
20	13	1	t. 13-1	103,36	25	1000	950578
21	14	5	t. 14-5	35,44	25	1000	950578

4.4.1 - Topology

Segment	Filled automatically according to the number of links
Upstream Node	For each segment, the user must select the starting node from the list (in each cell)
Downstream Node	For each segment, the user must select from the available list (in each cell) the node where the segment ends
Name	Filled in automatically to name the segments

4.4.2 - Decision variable

This has to be optimized in the solver or guessed as a first initial estimate. See Section X for more details.

4.4.3 - Geometry

$l\ [m]$	Pipe/segment length
$Real\ Diameter\ [mm]$	Pipe Internal Diameter
Cost (USD) fitted	Pipe cost calculated based on the cost function, pipe length and the internal diameter. For more information on the cost function, see the original paper HERE.

4.5 - Mass and energy balance minitabs

The mass balance is conducted by filling in the mass balance matrix in the Mass_Balance minitab, while the energy balance must be conducted by filling in the Energy_Balance minitab. Note that the number of rows and columns will be automatically populated based on the values of the number of links, nodes and loops inserted in the section "**4.2 - Defining the** initial parameters".

4.5.1 - Mass balance matrix

The matrix F_d represents the connection of every node with respect to the links, such that:

$$F_d(i,j) = \begin{cases} -1, & \text{if pipe j leaves juntion i} \\ 0, & \text{if pipe j is not connected to juntion i} \\ +1, & \text{if pipe j enters junction i} \end{cases}$$

The values must be filled in for each node following the convention that inlet pipes are positive and outlet pipes are negative. For the network shown in Figure 1, the matrix for mass balance should be filled as presented in Figure 9.

For example, node 1 receives the flow Q20 (coming from the reservoir) and has the outflows of Q1 and Q9. Therefore, for the row corresponding to node 1, the column related to Q20 should have a value of +1 (indicating that the flow enters the node). For the columns corresponding to Q1 and Q9, the value should be filled with -1 (indicating that the flow exits the node). All other values in this row should be filled with 0, as the other links have no physical relationship with this node (Figure 9).

Figure 9 - Mass balance matrix example.

Mass Balance Matrix

Fill values of each node following the convetion that inlet pipes are positive and outlet pipes are negative

Σ	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Node	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16	Q17	Q18	Q19	Q20	Q21
1	-1	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	1	0
2	1	-1	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0
3	0	1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0
4	0	0	1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0
5	0	0	0	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1
6	0	0	0	0	-1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
7	0	0	0	0	0	-1	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0
8	0	0	0	0	0	0	-1	1	0	0	0	0	0	1	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	-1	1	-1	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	1	-1	0	0	-1	1	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	1	-1	0	0	0	-1	1	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	1	-1	0	0	0	0	-1	1	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1

4.5.2 - Energy balance matrix

The matrix F_l represents the relation between the directions of loops and flows, such that:

$$F_l(i,j) = \begin{cases} -1, & \text{if pipe j is in loop i and their directions are opposed} \\ 0, & \text{if pipe j is not in the loop i} \\ +1, & \text{if pipe j is in loop i and their directions are the same} \end{cases}$$

The values must be filled in for each loop. For the network shown in Figure 1, the matrix should be filled as presented in Figure 10. For example, loop number 3 (nodes 3-4-12-11) in the network of Figure 1 contains four pipes (with flows Q3, Q19, Q12, and Q17). As defined earlier, loops always follow the clockwise convention. Therefore, for the columns corresponding to Q3 and Q19, the value to be filled should be +1 (indicating that the flow has the same direction as the loop). Whereas for the columns corresponding to Q12 and Q17, the value should be -1 (indicating that the flow has the opposite direction to the loop). For all other columns not related to the loop represented by this row, the value should be equal to 0.

Figure 10 - Energy balance matrix example.

Loop Incidence Matrix

Fill the connection within each loop. Pay attention with the signal of the pipes

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Loop	hf1	hf2	hf3	hf4	hf5	hf6	hf7	hf8	hf9	hf10	hf11	hf12	hf13	hf14	hf15	hf16	hf17	hf18	hf19	hf20	hf21
1	1	0	0	0	0	0	0	0	-1	-1	0	0	0	0	1	0	0	0	0	0	0
2	0	1	0	0	0	0	0	0	0	0	-1	0	0	0	-1	0	1	0	0	0	0
3	0	0	1	0	0	0	0	0	0	0	0	-1	0	0	0	0	-1	0	1	0	0
4	0	0	0	1	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	-1	0	0
5	0	0	0	0	0	0	0	-1	0	1	0	0	0	1	0	0	0	0	0	0	0
6	0	0	0	0	0	0	-1	0	0	0	1	0	0	-1	0	1	0	0	0	0	0
7	0	0	0	0	0	-1	0	0	0	0	0	1	0	0	0	-1	0	1	0	0	0
8	0	0	0	0	-1	0	0	0	0	0	0	0	1	0	0	0	0	-1	0	0	0

4.6 - Running a Hydraulic Simulation Problem (HSP)

4.7 -Running a Design Optimization Modeling (DOM)